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Parametrization of diabatic processes in the inversion of the omege-equation

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PARAMETRIZATION OF DIABATIC PROCESSES IN THE INVERSION OF THE OMEGA-EQUATION

by

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ABSTRACT

This Technical Report introduces an improvement to the parametrization of diabatic processes in the inversion of the quasi-geostaophic omega-equation.

It was found that the currently used algorithm sometimes produces predictions of vertical velocities due to diabatic processes which are in excess, in places, of the total model vertical velocities. This is due to the fact that the omega-equation does not always remain elliptic with the currently used algorithm. Corrective action is taken by setting the moist static stability parameter, σ_m, a small fraction of the dry static stability, σ, when the former becomes negative i.e., $\sigma_m = C\,\sigma$ (C is a constant) when $\sigma_m < 0$.

The new algorithm was tested for a range of different values of the constant C, from C=0.1 to C=0.01. The results show that the choice of the constant C does not significantly affect the retrieved vertical velocities. On the other hand, such corrective action is necessary in order to obtain realistic vertical velocities due to diabatic processes from the inversion of the omega-equation.

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1. INTRODUCTION

The quasi-geostrophic (QG) omega-equation is a useful tool to investigate processes affecting synoptic-scale vertical motions. From the different forms of the QG omega-equation that have been developed the Q-vector form is the most "compact" since in this formulation, the vertical velocity is forced solely by the divergence of $\bar{Q}$, (Hoskins et al. 1978, Clough et al. 1995).

Numerical inversion of the QG omega-equation with appropriate boundary conditions enables us to quantify the contributions from the different mechanisms (synoptic, diabatic etc.) to the total vertical motion, so that the relative importance of the different processes can be evaluated. Case studies have shown the importance of diabatic heating in the enhancement of vertical motions, (e.g. Krishnamurti 1968b, Clough and Davitt 1994, Athanassiadou and Thorpe 1995).

Here, the contribution of diabatic processes to the total vertical motion is re-examined. The QG omega-equation is solved using data from the Unified Model at a horizontal resolution of ~ 100 *Km*, and a vertical resolution of 100 *mb* from 1000 *mb* to 100 *mb*.

In section 2, the Q-vector form of the omega-equation and the method of solution is highlighted. In section 3 the current formulation of the algorithm that treats diabatic forcing is presented. The new improved code is also given in section 3. Sensitivity tests and comparisons are given in section 4. In section 5, an overview of the results and a discussion is presented.

2. THE OMEGA-EQUATION AND METHOD OF SOLUTION

The Q-vector form of the QG ω-equation in pressure coordinates, with diabatic and frictional effects included is given by:

$$\nabla_p^2\,\sigma(p)\omega + f_o^2\frac{\partial^2\omega}{\partial p^2} = -2\nabla_p\cdot\bar{Q} - \frac{R}{p}\nabla_p^2\left(\frac{\dot{q}}{c_p}\right) - f_o\bar{k}\cdot\left(\nabla_p\times\frac{\partial F}{\partial p}\right) \qquad (1)$$

where,

$$\bar{Q} = -\frac{R}{p}\left(\frac{p}{p_o}\right)^k \begin{pmatrix} \frac{\partial \bar{v}_g}{\partial x}\cdot\nabla q \\ \frac{\partial \bar{v}_g}{\partial y}\cdot\nabla q \end{pmatrix} \quad ; \quad \sigma(p) = -\frac{R\bar{T}(p)}{p}\frac{\partial \ln \bar{q}(p)}{\partial p} \qquad (2)$$

F stands for friction in general and $\dot{q}$ is the diabatic heating rate.

Equation (1) is solved in the "free"-atmosphere. In this case friction on the rhs of (1) is taken $F = 0$. Terrain and frictional effects are nevertheless enter through the lower boundary conditions. In general, frictional effects can be significant not only near the ground but at upper levels as well, near strong jets and in regions of deep cumulus convection.

The operator $\mathcal{L} = \nabla_h^2 + (f_o^2/\sigma)\left(\partial^2/\partial p^2\right)$ in (1) is linear since σ and f_o^2 are not functions of ω or derivatives of ω. In the quasi-geostrophic theory σ must only depend on p. Currently σ is evaluated as a horizontal average of the local values of static stability. Furthermore, equation (1) is elliptic provided that $-4(f_o^2/\sigma) < 0$ that is, when $\sigma > 0$ (statically stable atmosphere).

The problem of the QG ω-equation inversion consists of the solution of a linear PDE equation with appropriate boundary conditions. The schematic diagram in Fig. 1 summarises the procedure. In its general form, this problem is non-homogeneous in two ways; due to the forcing function $\mathcal{D}$ on the rhs of (1) and the boundary conditions $\mathcal{A}$. The vertical velocity ω can be decomposed into two parts, $\omega = \omega_1 + \omega_2$, one ω_1 due to the forcing $\mathcal{D}$ and the other ω_2 due to the boundary condition. It is easily checked that $\omega = \omega_1 + \omega_2$ satisfies the original equation and the non-homogeneous BC.

The solution for ω_2 can be further decomposed into $\omega_2 = \omega_{2sb} + \omega_{2mt}$, one ω_{2sb} due to the lateral BC and a ω_{2mt} due to the lower BC. Furthermore, the solution for ω_1 can be further decomposed into $\omega_1 = \omega_{1so} + \omega_{1dh}$, one ω_{1so} due to the synoptic scale only (dynamic) forcing and a ω_{1dh} due to diabatic heating. The forcing function of the later is associated with all processes except for dry adiabatic ascent and descent. In general, it contains two components of heating: (a) that due to diabatic processes such as radiation, turbulent mixing, surface sensible heating and cumulus convection ($\mathcal{D}_{ND}$), nor resolved by the model data; and (b) that resulting from resolved moist adiabatic ascent ($\mathcal{D}_{MA}$).

The partitioning described thus far has the feature that

$$\omega = \omega_{1so} + \omega_{1dh} + \omega_{1sb} + \omega_{2mt} = \omega_{1sc} + \omega_{1nd} + \omega_{1ma} + \omega_{2sb} + \omega_{2mt} \qquad (3)$$

so that the total vertical velocity ω can be decomposed into different parts, each being the contribution to the vertical motion from different, interrelated nevertheless, mechanisms. The above decomposition is not the only one possible, but it is the one that gives more insight into the role of individual processes.

2.1 Diabatic forcing (latent heat release)

In general, $\dot{q} = \dot{q}_{ma} + \dot{q}_{nd}$; where $\dot{q}_{ma}$ is due to moist ascent and $\dot{q}_{nd}$ is due to all forms of heating (or cooling) not resulting from dry or moist adiabatic ascent or descent in synoptic-scale systems.

The ω component associated with diabatic heating will be assumed only associated with diabatic heating from latent-heat release in regions of precipitation $\dot{q}_{ma}$. This is considered the dominant process for synoptic-scale vertical motions. Indeed, in limited areas of heavy precipitation, condensation heating can easily surpass 1 *K/h* in deep layers (assuming a precipitation rate of 4 *mm/h*), whereas radiative cooling, for example, seldom exceeds a few degrees per day. Typically, strong condensation heating induces a core of intense rising motion and a wider surrounding belt of weak subsidence.

The ω component that is associated with latent heat release is the solution to

$$\nabla_p^{\,2}\,\sigma(p)\omega_{ma} + f_o^2\frac{\partial^2\omega_{ma}}{\partial p^2} = -\frac{R}{p}\nabla_p^{\,2}\left(\frac{\dot{q}_{ma}}{c_p}\right) \quad ; \quad \omega_{ma} = 0 \quad \text{(BC)} \qquad (4)$$

Therefore ω_{ma} represents the *"enhancement"* in the vertical motion due to the fact that ascent takes place on a saturated environment.

To find the contribution to the vertical motion from diabatic heating it is necessary to evaluate $\dot{q}_{ma}$. Generally this is not an observed quantity so that it must be diagnostically calculated. It is often the case (for ascent following a moist adiabat) that $\dot{q}_{ma}$ can be related to the vertical motion itself. So we can express the diabatic heating rate per unit mass associated with moist ascent as:

$$\dot{q}_{ma} = \begin{cases} -L\dfrac{\partial q_s}{\partial p}\omega, & \text{when the air is saturated and rising} \\ 0 & \text{otherwise} \end{cases} \qquad (5)$$

A better alternative is to find $\dot{q}$ used in the model initialisation or forecast. As this is not available routinely, equation (5) is a practical and straightforward way to estimate $\dot{q}$.

Equation (4) is therefore written as

$$\nabla_p^{\,2}\,\sigma(p)\omega_{ma} + f_o^2\frac{\partial^2\omega_{ma}}{\partial p^2} = \frac{RL}{c_p\,p}\nabla_p^{\,2}\left[\frac{1}{2}(\omega - |\omega|)\frac{\partial q_s}{\partial p}\right] \qquad (6)$$

A static stability parameter for moist air can be given in terms of the equivalent potential temperature as:

$$\sigma_m(p) = -\frac{R\overline{T}(p)}{p}\frac{\partial \ln\overline{\theta}_e(p)}{\partial p} \quad ; \quad \overline{\theta}_e = \overline{\theta}\exp(Lq_s/c_p\overline{T}) \qquad (7)$$

Moreover, the relation between σ and σ_m can be obtained from (2) and (7):

$$\sigma_m = \sigma - \frac{\delta RL}{c_p\,p}\frac{\partial q_s}{\partial p} \quad ; \quad \delta = \begin{cases} 1, & \text{for } q = q_s \ \wedge\ \omega < 0 \\ 0 & \text{for } q < q_s \ \vee\ \omega > 0 \end{cases} \qquad (8)$$

and (6) can be written as:

$$\nabla_p^{\,2}\,\sigma_m(p)\omega_{ma} + f_o^2\frac{\partial^2\omega_{ma}}{\partial p^2} = \frac{RL}{c_p\,p}\nabla_p^{\,2}\left[\frac{1}{2}(\omega_R - |\omega_R|)\frac{\partial q_s}{\partial p}\right] \qquad (9)$$

where $\omega_R = \omega - \omega_{ma}$ is the (synoptic-scale) part of vertical motion due to all processes apart from the latent heat release. Equation (9) remains elliptic as long as $\sigma_m > 0$. Note that although σ is only a function of p, the quantity σ_m can and does also vary in the horizontal.

Equations (6) and (9) are alternative forms giving the same contribution ω_{ima}. It is clear that the interpretation of ω_{ima} is that it is the *additional* vertical motion that exists because the atmosphere locally is saturated and releases latent heat. It represents an amplification of that part of the vertical motion which exists due to synoptic-scale forcing in a dry atmosphere.

Note that the inherent significance of this additional contribution ω_{ima} is not diminished by using the model total ω to evaluate $\dot{q}$.

3. THE NEW IMPROVED CODE

3.1 Current method of solution

The inversion of the omega-equation is among the diagnostics available from the Unified Model. This is done with the MDIAG - set of programmes. Current settings include zero vertical velocity at all boundaries.

Diabatic processes are parametrized in a manner analogous to the one described in Section 2. In particular, the vertical velocity associated with latent heat release is obtained from:

$$\nabla_h^{\,2}\,\sigma(p)\,\omega_{ima} + f_o^2\,\frac{\partial^2\omega_{ima}}{\partial p^2} = \frac{RL}{c_p p}\nabla^2\left(\omega_{MODEL}\,\frac{\partial q_s}{\partial p}\right) \quad ; \quad \omega_{ima} = 0 \quad \text{(BC)} \qquad (10)$$

following the procedure described below.

The ω in the forcing term is taken from the model output. Generally $\omega_{MODEL} \neq \omega$ and in that respect, the diabatic forcing term somewhat differs from the approach in section 2. This is because ω_{MODEL} embodies vertical motion due to all possible physical processes, even those not included in the quasi-geostrophic omega equation. Different values of L are assumed depending on whether the temperature is above or below zero. Moreover, both negative and positive values of ω enter the rhs of (10) and the diabatic forcing is zero, only when the RH with respect to ice is less than 85%.

3.2 Suggested method of solution

Proper solution of the omega-equation requires that (10) remains always elliptic. In turn, this requirement is satisfied when the effective static stability $\sigma_m = \sigma - \frac{RL}{c_p p}\frac{\partial q_s}{\partial p}$ is always positive. This condition though, is not satisfied everywhere. The unrealistic vertical velocities due to diabatic forcing which are obtained from the inversion of the omega-equation are believed to exist because of the violation of the requirement $\sigma_m > 0$.

When $\sigma_m < 0$ but $\sigma > 0$, the atmosphere is conditionally unstable and the parametrization of the diabatic processes needs a different formulation (Krishnamurti 1968a). In the improved scheme, proposed here, an adjustment is made to the effective static stability σ_m when this becomes negative. The adjustment consists of setting the effective static stability equal to a small number times the static stability when the former is negative.

$$\sigma_m < 0 \quad \Rightarrow \quad \sigma_m = C\,\sigma \quad ; \quad C = const. \tag{11}$$

This is equivalent to the neglect of conditionally unstable regions. The choice of a reasonable value for C is not obvious, apart from the fact that it should be a small number. Different values of C where considered in the range 0.1 to 0.01. The new scheme was tested for the case studies of the ANOMALIA project (Athanassiadou and Thorpe, 1996). Results from one of the case studies, using the new scheme, are presented in the next section.

4. RESULTS

Model vertical velocities as well as vertical velocities obtained from the inversion of the omega-equation with both the old and the new scheme are shown for the 12Z of the 23/9/93 on the 700 *mb*. The experiments using the new scheme are summarised in Table 1.

Fig. 2 shows the vertical velocity w_{MODEL}, the model output. Solid and dotted contour lines in this figure, as well as subsequent ones, encompass vertical velocities $\geq 2\ cm\ s^{-1}$ and $\leq -2\ cm\ s^{-1}$ respectively. Two points, A and B, are chosen to facilitate the inter comparison of the results. Point A is over the Atlantic (x=2438.4 y=812.8), in the area of maximum ascent.

Point B is over the western Mediterranean (x=5791.2, y=914.4). The results are summarised in Table 2.

Experiment	name	$\sigma_m = C\,\sigma$	Diabatic forcing ≠ 0 when RH > 85% and
1	ns	C=0.1	$\omega < 0$ only
2	nl	C=0.01	$\omega < 0$ only
3	si	C=0.01	$\omega < 0$ and $\omega > 0$

Table 1: Summary of the settings for the experiments performed with the new scheme.

Point	A	B
w_{MODEL} *cm/s*	16.6	14.1
w (old scheme) *cm/s*	22.8	17.4
w (ns) *cm/s*	13.1	10.6
w (nl) *cm/s*	14.4	11.6
w (si) *cm/s*	14.5	11.6
w (synoptic forcing) *cm/s*	~0.0	1.4

Table 2: Vertical velocities for points A and B, from the model and the inversion of the omega equation using the different schemes. Also given is the calculated vertical velocity from the synoptic forcing.

The vertical velocity calculated from the inversion of the omega-equation using the old scheme is shown in Fig. 3. This, as well subsequent figures show just the diabatic contribution. Although the overall pattern seems quite reasonable, closer inspection of the maximum values of w, in Fig. 3, reveals that, in places, these are in excess of the w_{MODEL}. In particular, the vertical velocity using the old scheme is 37% in excess of w_{MODEL} at point A and 24% at point B. This does not seem a very realistic solution.

In the first of the experiments performed with the improved scheme (ns), the effective static stability was set equal to 0.1 times the static stability when the former became negative. The vertical velocity from the inversion of the omega-equation for the experiment ns, is shown in Fig. 4.

With the new algorithm, the vertical velocity due to diabatic processes w_{ma}, is realistic. Nowhere in the domain w_{ma} exceed w_{MODEL}. In particular, w_{ma} at points A and B are 79% and 75% of w_{MODEL} at the same points respectively. Clearly this is an improvement to the existing algorithm toward realistic vertical velocities due to diabatic forcing.

The sensitivity of the solution to the choice of the constant C used in the new formulation was examined for a variety of different values of C. Fig. 5 shows the results from the second experiment (nl) in which C=0.01, an order of magnitude smaller than it was in the first experiment (ns). The overall pattern of w_{ma} in Fig. 5 is almost identical to the one in Fig. 4 (experiment ns). Slightly larger values are obtained in this case at points A and B compared with the values obtained at the same points in the experiment ns. In particular, w_{ma} at A is now 87% and at B 82% of w_{MODEL}. This amounts to a difference of the order of 7-8% between the two cases.

Finally, one further test was performed in order to assess whether the diabatic forcing should be evaluated for rising air only or for both rising and descending motion. This latter case might be relevant if evaporation of precipitation is effective. As the diabatic forcing is only used on descent for RH $\geq$ 85%, then this may be a realistic representation. The results from this third experiment (si), are shown in Fig. 6. The constant C in this case is C=0.01 so that comparisons should really be made with Fig. 5 (experiment nl) and Fig. 2 (the model vertical velocity).

The overall pattern of ascending w_{ma} virtually identical to the one of the experiment nl. This is also true for the maximum values of the obtained updrafts, Table 2. The only difference between the experiments nl and sl is in the obtained downdrafts. This is particularly the case in the western Mediterranean region, behind the strong frontal system in the area (not shown but somewhat obvious from the vertical velocity pattern in Fig. 2).

5. DISCUSSION

It is clear from the results presented in the previous section that the existing code needs to be adjusted if reasonable vertical velocities due to diabatic forcing are to be obtained from the inversion of the QG omega-equation. With the currently employed algorithm, the omega-equation does not remain elliptic throughout the domain where solution is sought.

The simple solution to the problem, suggested in this report has shown that reasonable results can be obtained by setting the effective static stability equal to a small constant times the static stability, when the former becomes negative. Under this approach, conditionally unstable regions are neglected. A more advanced improvement, and probably a better one, would be to parametrize appropriately, moist processes under unstable conditions. This is left as future research.

Finally, it seems better to apply the parametrization to both rising and descending motion as long as the diabatic forcing is only evaluated for nearly saturated air. The main difference between this and restricting diabatic forcing to rising motion is in the downdrafts, especially behind strong frontal systems, calculated from the inversion of the omega-equation.

6. ACKNOWLEDGEMENTS

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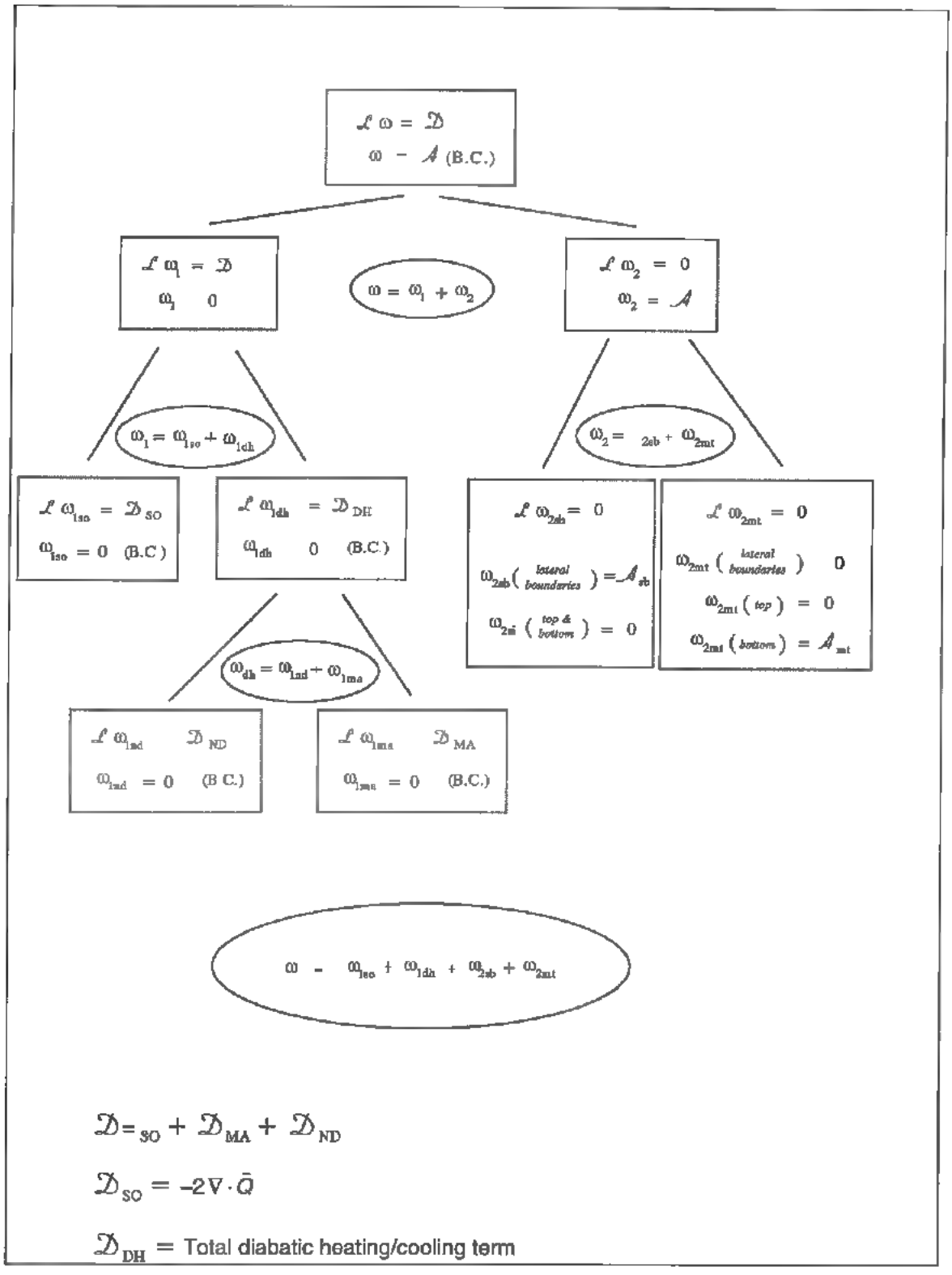
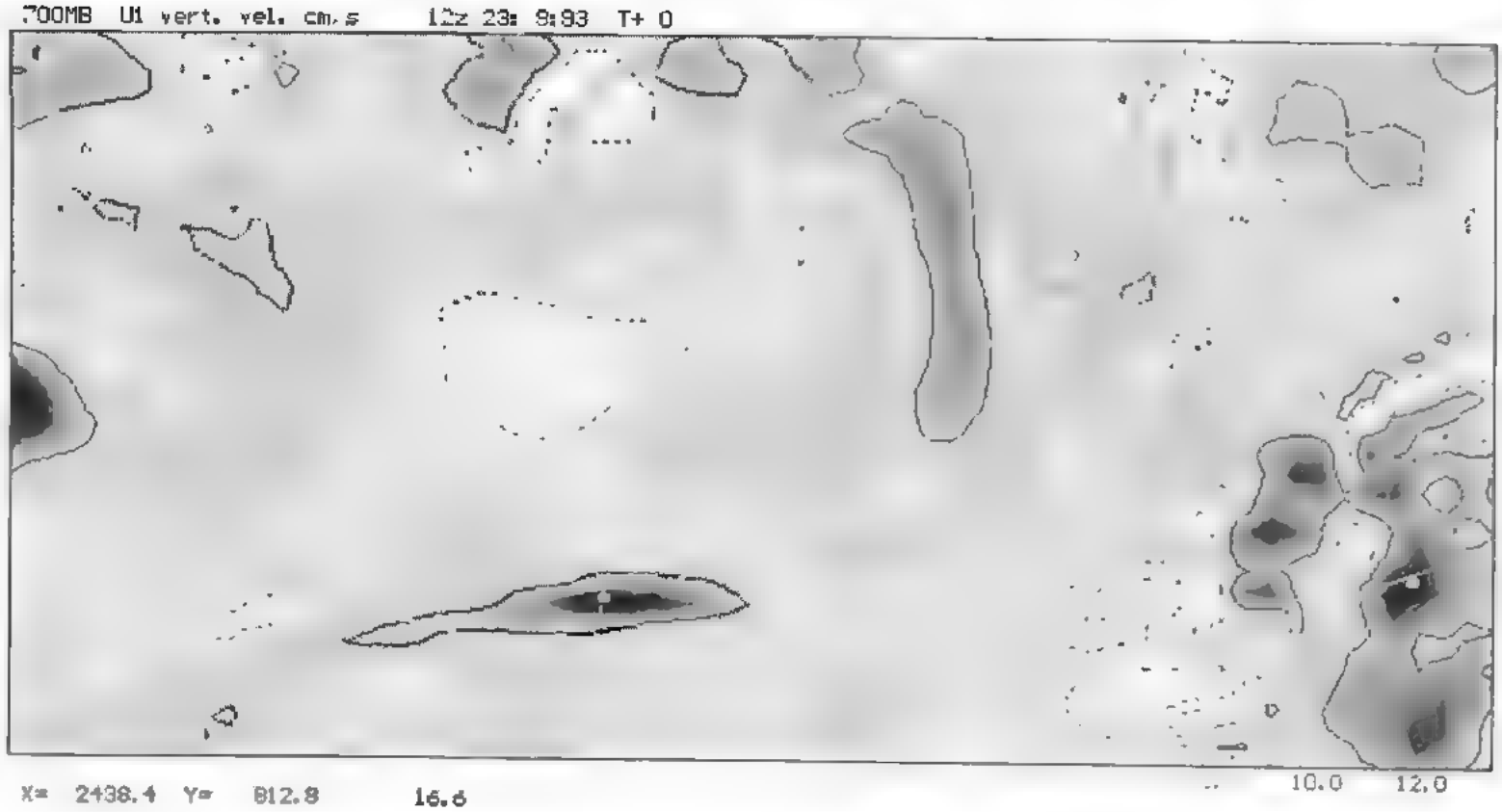
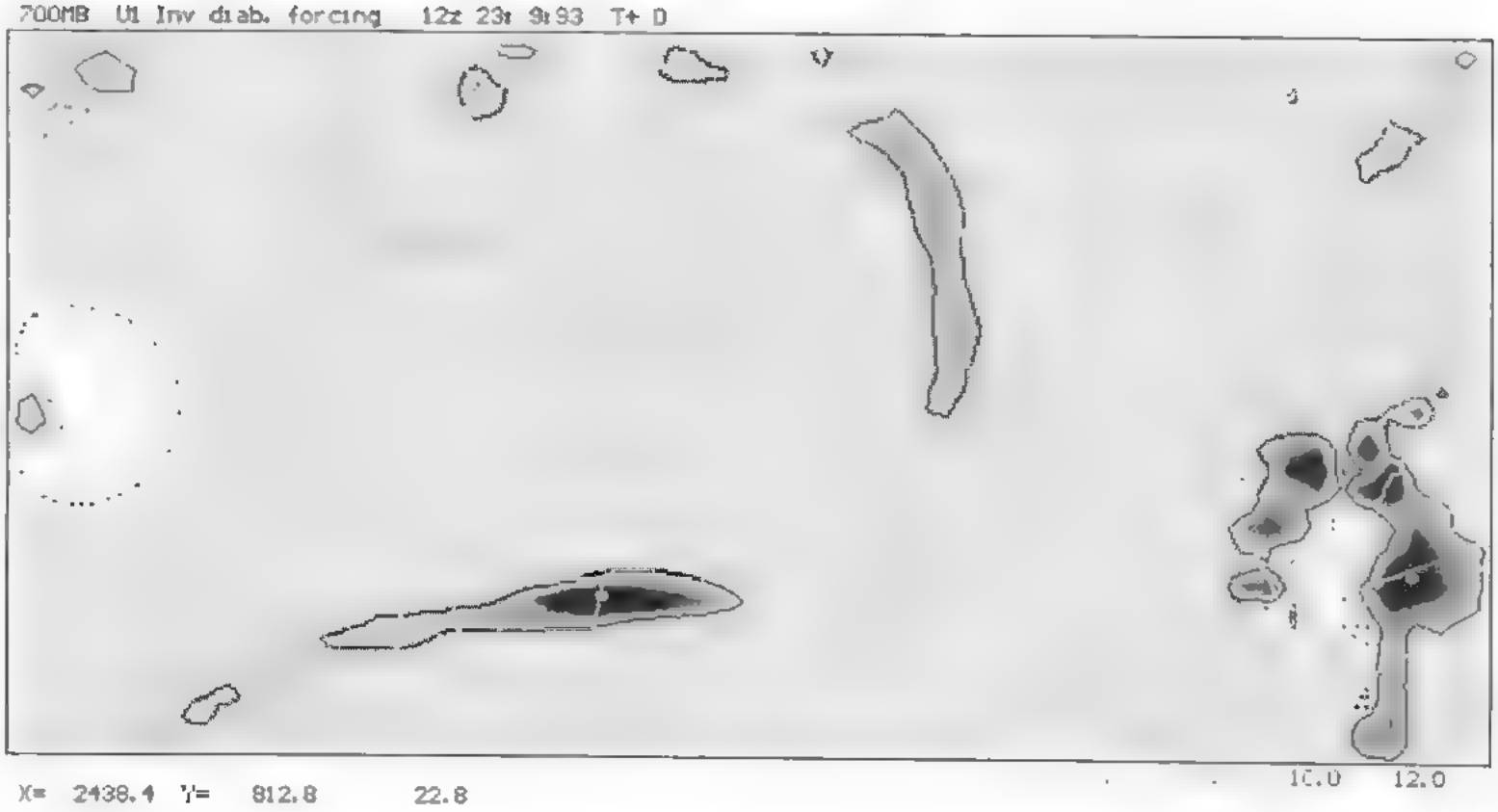


Figure 1: Schematic diagram of the solution of the omega-equation in general



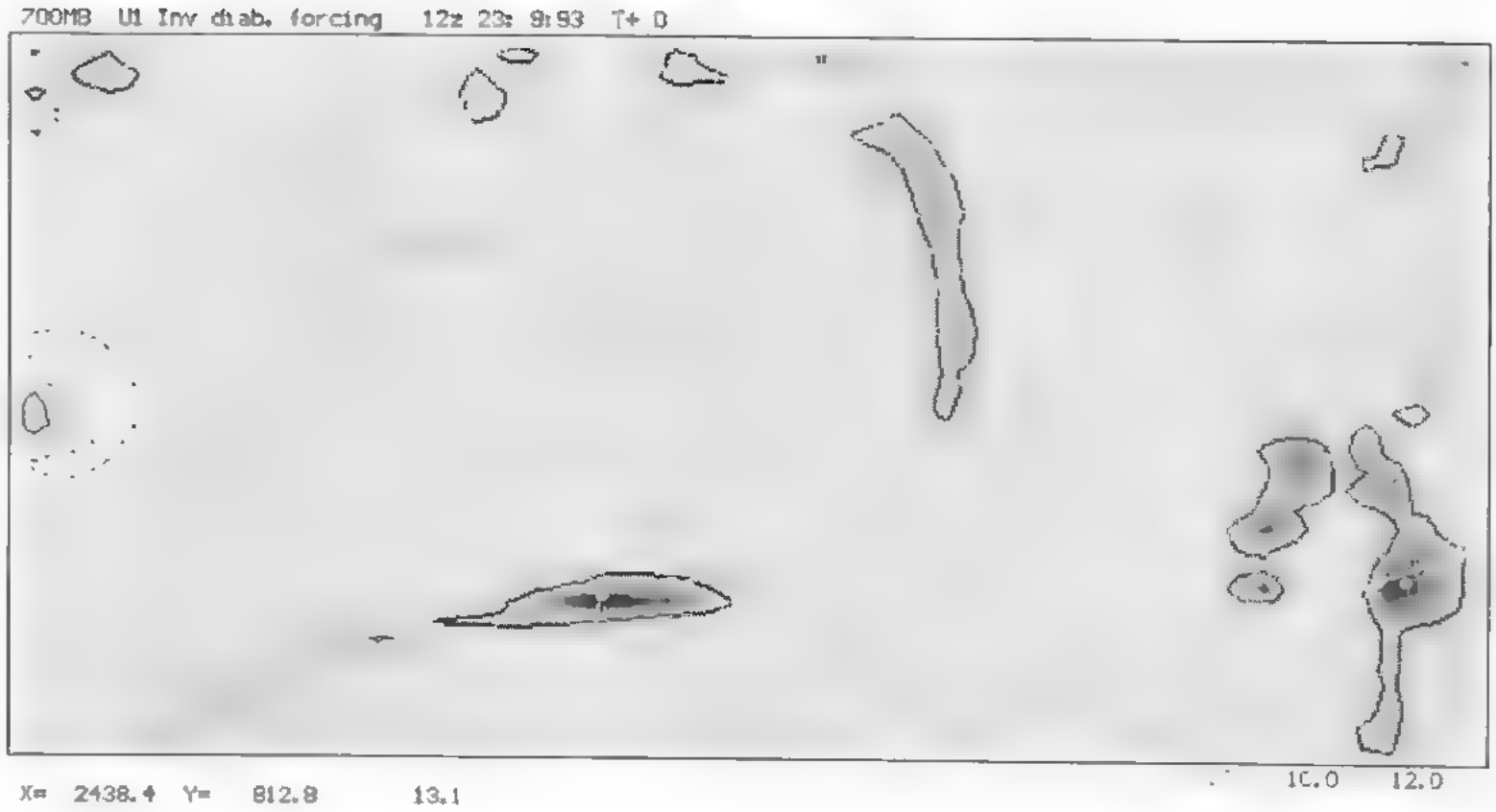
MODEL VERTICAL VELOCITY

Figure 2: Vertical velocity. Contours: Solid 2 cm/s. Dotted -2 cm/s



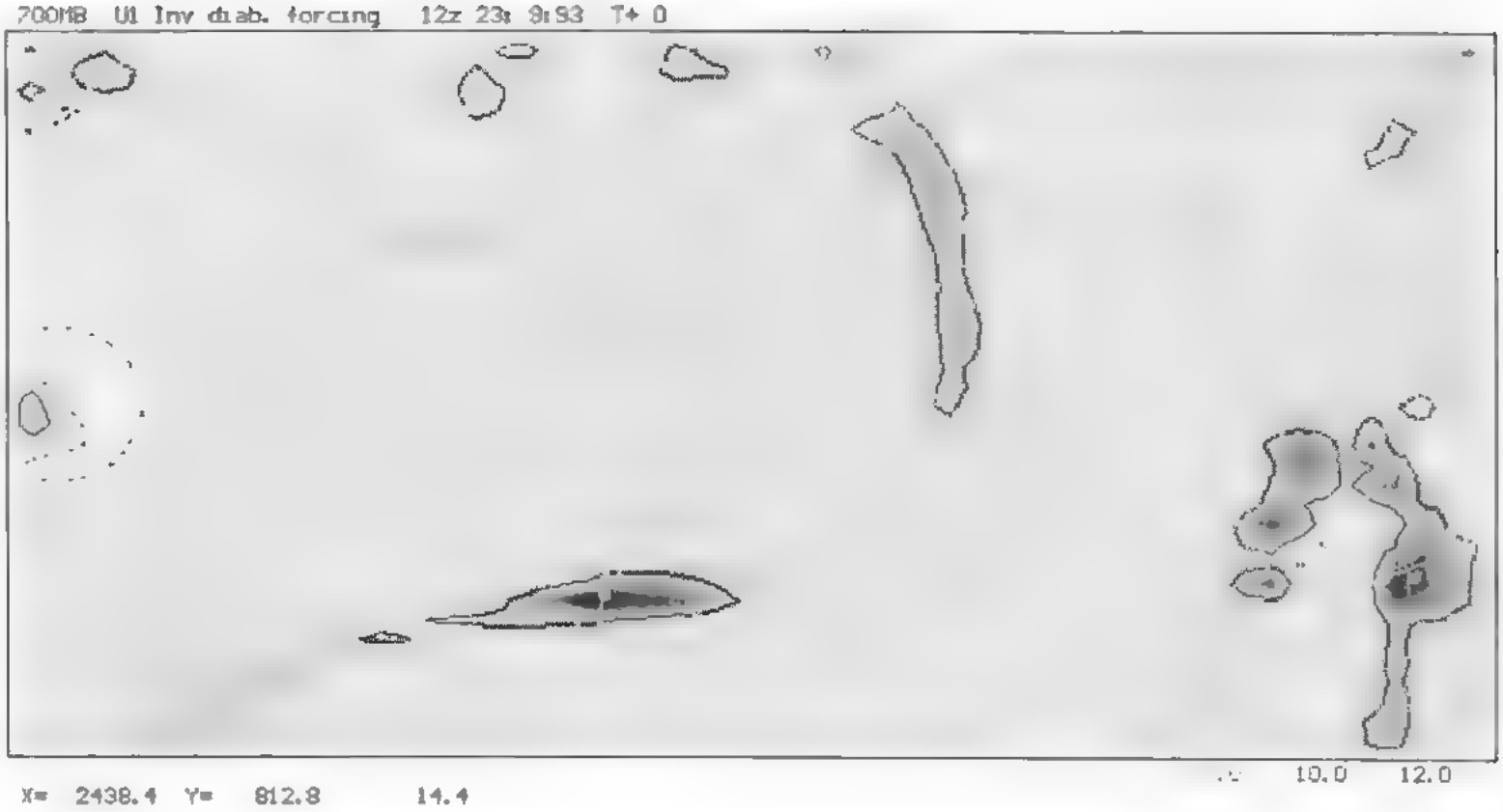
OLD SCHEME

Figure 3: Vertical velocity. Contours: Solid 2 cm/s. Dotted -2 cm/s



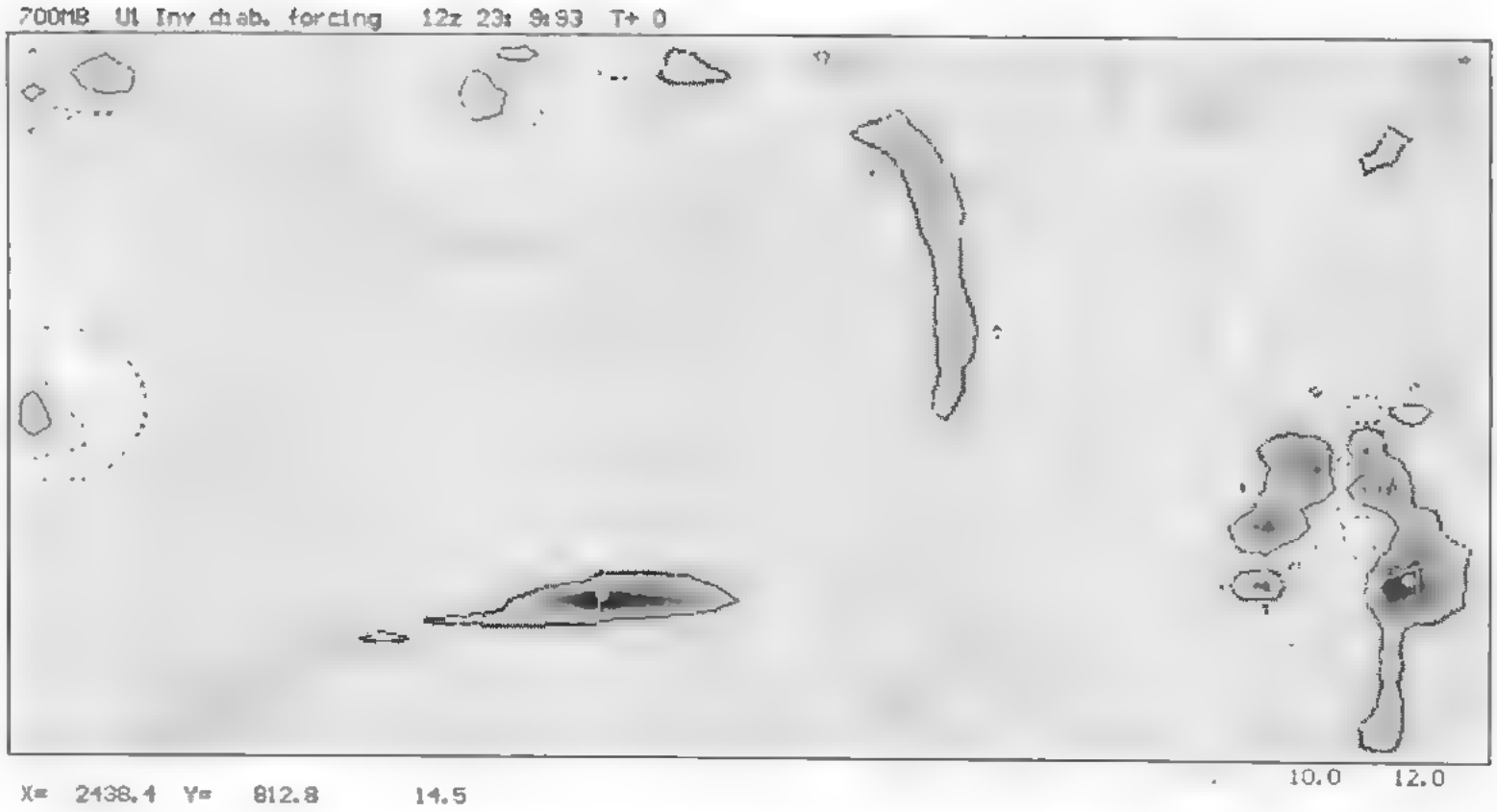
EXPERIMENT 1 (ns)

Figure 4: Vertical velocity. Contours: Solid 2 cm/s. Dotted -2 cm/s



EXPERIMENT 2 (nl)

Figure 5: Vertical velocity. Contours: Solid 2 cm/s. Dotted -2 cm/s



EXPERIMENT 3 (si)

Figure 6: Vertical velocity. Contours: Solid 2 cm/s. Dotted -2 cm/s

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